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Synopsis: In this paper the main results obtained in the research program "High Performance Concretes in the 90'es" are presented. This program was financed by the Danish government and was carried out in cooperation between The Technical University of Denmark, several private companies and Aalborg University. The paper includes the results with regard to mix design, uni- and triaxial strength, creep, shrinkage and chloride diffusion of HPC.

Further the paper gives a brief description of the bridge structures in Denmark in which HPC has been utilized. These structures include pedestrian bridges, highway bridges and major infrastructure schemes such as the Great Belt Link and the Øresund Link.

Finally the paper states the research areas which, according to the experiences in Denmark, should be investigated in the future in order to improve HPC. These areas include the strength loss of silica concretes, workability, ductility- and confinement problems.

Keywords: Chloride diffusion; confinement; creep; high performance concrete; high strength concrete; mix design;shrinkage; silica concrete; triaxial strength; Applications of high performance concrete.

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INTRODUCTION

The Danish code for the use of structural concrete has a limit of 50 MPa on the level of the characteristic strength of concrete which can be taken into account in the design of structures. Nevertheless several structures have been built in the last 5 to 10 years with stronger concretes, either in order to achieve a dense concrete well suited for harsh environmental conditions or as experimental structures built as part of research programs.

The experience in Denmark with regard to high performance concrete (HPC) can be categorized in three groups. A number of research programs have been undertaken in resent years in order to investigate the material properties of HPC. Partly these investigations have had the aim to provide the knowledge base from which the code limit could be raised. Furthermore a number of relatively short span bridges have been built utilizing HPC in order to obtain knowledge on the full scale level with regard to the structural behavior as well as the durability characteristics. Finally two major infrastructure projects are under construction, the Great Belt Link and the Øresund Link, which incorporate the use of HPC in order to assure a specified design life of the structures of 100 years.

FUNDAMENTALS

Mix Design

The concretes dealt with in this paper are made with ordinary constituents of a good quality. The materials fulfil the requirements in the environmental class A in [1]. Three types of portland cement were used: PC(R/IS/MA/G) compareable to ASTM type III; PC(A/HS/EA/G) compareable with ASTM type IV-V; PC(R/HS/EA/W) compareable with ASTM type III-IV. Silica fume supplied as slurry 50%/50% w/w was used in all mixes. Silica fume as dry condensed particles has been found to result in undesired lumps of silica in the hardened concrete. Pulverized fuel ash (fly ash) supplied as dry powder was used in most mixes. Water-reducing admixtures of ASTM type A and type D were used together with superplasticizers. In some cases even air-entraining agents were used to improve the workability or frost resistance.

The fine aggregates are normally quartz from the Danish territory. The coarse aggregates can be either crushed rock from the Danish island of Bornholm, sea dredged gravity sorted rounded materials, collected crushed field rocks (granite boulders) or crushed rocks imported from Sweden, Norway or Scotland. The maximum particle size is normally 16 mm if the strength requirements are critical or 32 mm if the durability is critical. The use of theoretical packing analysis for determining the void space of the aggregates is making progress in Denmark. The advantages of being able to calculate the void space are obvious. Less cement paste is needed to achieve satisfactory consistency, increased stability of the aggregate body and finally savings in the number of trials to hit a satisfactory composition are obtained.

The combination of three powders is believed to improve the performance of the fresh as well as the hardened concrete. In [2] the permitted limits of silica fume and fly ash are respectively 10- and 35 per cent by mass of the total powder. However, for practical purposes the contents are normally lower. This is due to the points discussed below. The consistency of the fresh concrete is normally affected adversely, if the content of powder, especially silica fume, is too high. Furthermore, the strength development is normally affected adversely, if the content of fly ash exceeds a certain level. The micro structure studied by flourescent thin sections is affected adversely, already at early ages, if the powder combination is improper e.g. too much or too little silica fume and/or fly ash.

The micro structural analyses suggest that the limit of 10 per cent silica fume by weight should not be exceeded nor should it be too close to the limit. As discussed later the lower limit for the content of silica fume should be arround 5 per cent of the powder, if good durability performance in saline environments is required. The lower limit of the recommended fly ash content is chiefly governed by the wish of a homogenous and crack free micro structure. A powder consisting of cement and silica fume and no fly ash may exihibit a tendency of intensive micro cracking at early ages (1-2 months), while a combination of all three powders may result in an almost micro crack free concrete, at the same age. The upper recommended fly ash content is important if the strength requirements are important. The limits of puzzolana content used for most HPC bridges in Denmark are 10% to 15% fly ash and 5% to 8% silica fume; both given as percentage of total powder.

The cement matrix must be composed to meet the quality requirements e.g. low chloride diffusivity, sufficient strength and satisfactory micro structure. The flow characteristics of the fresh cement paste must meet workability requirements, which are optained by the grading of the aggregates, which may be adjusted in order to minimize the use of expensive admixtures. Reduction in the use of admixtures also reduces side effects such as long setting times and difficulties with casting sloping faces.

Chloride Ingress

Penetration of chlorides into non-fractured, water saturated concrete is assumed to obey Fick's 2nd law, which can be solved as a semi-infinite diffusion problem. The method developed for determining the concrete's resistance to chloride ingress, APM 302 [3], uses an artificial exposure of a core with a cut surface situated 10 mm below the original surface for at least 35 days in a NaCl-solution (165 NaCl/l). The chloride profile is determined by analyzing powder samples from well defined depths by means of a specially developed grinding technique, which makes it possible to make samples of layers with thicknesses down to 0.5 mm. The mathematical model is curve fitted to the chloride profile by optimizing the parameters of the model using a non-linear regression analysis. Usually the method [3] overestimates the chloride ingress rate in comparison to field observations. This is mainly due to two factors. The time dependency of the diffusion coefficient and the varying environments at different positions in a chloride exposed structure.

Together with the rate of diffusion, the level of the chloride concentration and the type of exposure (constant immersion or combined wetting and drying) are of major interest. Most of all, the chloride induced pitting corrosion is of interest. Many attempts have been made to determine the critical chloride concentration that will initate corrosion.

Recently a Danish and Swedish research cooperation has resulted in a testing method [4] for determination of critical chloride concentrations for all types of concretes. The method combines the accelerated test described above with the use of potentionstatic controlled preset potentials of mild steel bars in a corrosion cell. This makes it possible to estimate the dependency between the critical concentration and the corrosion potential, which in a real structure varies mainly with the access of oxygen to the cathodic areas. By monitoring the correlation between the diffusion coefficients and the true free potentials of the reinforcement, better lifetime estimates based on accellerated laboratory tests, will be possible in the future.

The present results predicts very long lifetimes before the isolated action of chlorides will affect the safety of the structures having covers of 50 mm or more. Hence in the future it may be possible to reduce the standard values when using HPC.

Uniaxial Stress Strain Curve of HSC and Crack Development

The aim of this part of the investigation was to observe the crack development during increasing strain. This part of the research program has been reported in the report [4] by Dahl.

All tests were performed by use of 100mm by 200mm cylinders. The test specimens were removed from the molds after approximately 24 hours and water cured for 13 days, after which the specimens were air cured for 14 days at 20°C and 60% RF. The tests were undertaken at a rate of 13 micro strain/second.

The crack development during loading was determined at 6 load levels on specimens of 70 MPa. The specimens were, after unloading at the predetermined point on the stress strain curve, cut vertically, polished and injected with an epoxy resin. The crack development was observed by use of a 40X microscope capable of detecting crack widths down to 0.005 mm. The observations of the crack development for the 70 MPa specimens were summarized in [4] as follows:

- In the pre-peak region some, but not many, micro cracks start forming. The micro cracks are mostly radiating from the aggregate particles.
- At peak load almost no finer cracks, $0.01\text{mm} < w < 0.1\text{mm}$, are visible.
- In the post peak region larger cracks start forming along the Coulomb lines, i.e. the failure lines predicted bu the Mohr-Coulomb failure condition. Large crack widths are observed in these cracks.
- In addition to these cracks, more finer cracks form in the center third of the specimen. The widths of these cracks stay below 0.2mm, and the orientation is vertical through both paste and aggregate particles.

Triaxial Strength of HSC

The scope of the investigation was to perform tests in a wide range of compressive strengths, varying from normal strength to more than 100 MPa, with the emphasis on the higher part of the strength range. Furthermore it was emphasized that the test series was performed including a wide range of the major principal stress. This part of the research program has been reported thoroughly in [6] and [7].

All tests were performed on 100mm by 200mm cylinders. The cylinders were removed from the moulds after 24 hours and cured 13 days in water followed by 14 days of air curing at 20°C and 60% RH. The specimens were cast in 7 nominal strength classes: 10, 35, 50, 70 , 85 100 and 110 MPa.

The tests were performed by using a triaxial cell capable of applying an oil pressure as active confinement. All tests in the investigation were performed by applying hydrostatic pressure up to a specified level, followed by an increase in the longitudinal (deviatoric) pressure until failure of the specimen. The load was in all cases applied at a rate of 0.3 MPa/s. For this load path the two largest principal stresses, σ_1 and σ_2 (possitive as tension), are equal, and the smallest principal stress, σ_3, is decreased (corresponding to an increase in compression) to failure. It should be noted that the load path may influence the failure envelope, and other methods of applying the confinement consequently can be expected to yield somewhat different results.

In order to validate the test results obtained in the investigation, Dahl [6] has compared the results obtained for low and normal strength concretes tested in the triaxial cell, with similar results obtained by Richart et. al.[11], Hobs [12] and Bellotti [13]. In all cases the results did not deviate to any considerable degree from the previous investigations.

During the testing it was observed that, in some cases with confining stresses above 100 MPa, the specimens did not fail in normal sence, but underwent large deformations both in longitudinal- and transversal directions without a complete drop of load bearing capacity. Consequently the tests in these cases were stopped by the deformation capacity of the test rig, and not by ordinary failure of the specimens. The results in the above mentioned cases have not been included in Figures 1 and 2, due to the absence of a definite failure.

From Figure 2 it will be noted that the test results of the high strength concretes do not conform to the normal Mohr-Coulomb failure criterion in the total range of confining stresses. On Figure 2 the lower part of the line corresponds to the normal Mohr-Coulomb failure criterion with friction angle $\varphi = 37°$. For confining stresses above 0.6 f_c this line is proceeded by a line corresponding to a friction angle of $\varphi = 28°$ and an imaginary uniaxial compressive strength of 1.8 f_c. From the test results presented in Figure 1 it is noted, that the test results of specimens of nominal strengths 10, 35 and 50 MPa show an increasing tendency to deviate from the normal Mohr-Coulomb failure criterion.

Above observations can be interpreted as an indication of the friction angle being reduced with increasing concrete strength up to about 70 MPa, after which the friction angle tends to stay constant. The change in inclination of the failure criterion could be interpreted as the level of confinement, at which the effects of internal micro cracking of the high strength concretes no longer influences the triaxial strength. Consequently, above mentioned imaginary uniaxial compressive strength of 1.8 f_c could be interpreted as the strength of a high strength cylinder completely free of internal micro cracking.

Creep and Shrinkage of HSC

In this part of the program, the scope was to investigate the shrinkage and creep of concretes of a wide range of compressive strengths, but with similar aggregate ratios. Furthermore it was emphasized, that the test period was to be approximately one year. The influence of the age at loading and the load level were parameters of special interest for the creep tests, as was the shrinkage as function of f_c and the autogenous shrinkage for the shrinkage tests on the high strength concretes. This part of the research program has been reported thoroughly in the reports [8]-[10] by Jensen.

The investigation was undertaken by application of thirty creep test rigs placed in a climate tent, in order to ensure well defined environmental conditions. By using the tent it was possible to assure a constant temperature of 21° and 65% RH.

The test specimens were three 100mm by 200mm cylinders placed on top of each other with an 100mm by 60mm "dummy" cylinder in each end between the test cylinder and the load plate, in order to establish the same boundary conditions for all of the three cylinders comprising a test specimen. The specimens were cast and left in the moulds for one day, after which 26 days of water curing and 2 days of air curing (during preparation for the tests) followed. Three tests were undertaken after only 8 days of curing for the investigation of the influence of age at loading on creep. Each creep test specimen was placed in a test rig and a similar unloaded specimen accompanied each creep test specimen, for determination of the shrinkage.

On figure 3 the creep of specimens of varying compressive strengths is shown. All of the tests have been performed at a load level of $\sigma/f_c = 0.3$. The high strength specimens show a creep after 11 months of approximately the half of the normal strength concrete specimens. These results correspond to the fact that high strength concrete has only a small amount of evaporable water and a dense structure of the paste.

Figure 4 shows the influence of the load level on the creep of HSC specimens. It can be seen that the load level has the same influence as for normal concrete, i.e. an increase in load level corresponds to an increase in creep.

The dependency on the creep as function of the age of the specimen at the time of loading is shown on figure 5. In order to compensate for the increase of strength of a given specimen from the 8th day to the 29th day, the specific creep of tests in this group, defined as ϵ/f_c, has been plotted. From the figure it will be noted that the level of specific creep for high strength concrete is roughly a factor 7 smaller than creep of normal strength concrete loaded at the same age. Furthermore it is evident that the effect of age at loading is the same for the high strength specimens as for the low strength specimens, i.e. decreasing the age at loading corresponds to increasing specific creep.

On figure 6 the shrinkage of 7 specimens similar to the creep specimens on figure 5 is shown. It is evident that the shrinkage is reduced with an increase in compressive strength given that the specimens, as in the test series, have almost the same content and type of aggregate and have been stored under the same environmental conditions.

The effect of the compressive strength on the autogenous shrinkage has been investigated by sealing three specimens. The effectiveness of the sealing has been checked by weighing the specimens. The sealing has not been found to be completely effective (especially for low strength specimen), thus the results shown on figure 7 should be regarded with some caution. From this figure it can be seen that the high- and very high strength specimens seem to have a higher level of autogenous shrinkage than the low strength specimens, which correspond to the low water content of the HSC and VHSC specimens.

APPLICATIONS

The Ryå Bridge

The use of HPC in Denmark started in the early 1980'es. The erection of the minor (a span of 7.5 m) experimental highway bridge over Ryå took place in 1981. Here the use of silica fume, as a mean to improve the durability performance of concrete mixed and placed in the traditional way, was introduced in Denmark. The experiences after 12 years of follow-up investigations on the performance of this bridge can be summarized as follows:

- Visual inspections did not show any changes in the initially developed thermo-cracks.
  There has been some abrasion of the unprotected and non-isolated slab superstructure that acts as carriageway.
- Compressive strengths measured on drilled cores have a large standard deviation and some results show only half of the original compressive strength.
- The number of microcracks ($< 10\ \mu m$) has increased from a fairly high initial level to a high level.
- The compressive strength depends on the number of microcracks.
- The chloride penetration due to the use of deicing salts (NaCl) is very low and diffusion coefficients of $0.5\text{-}1 \cdot 10^{-13}\ m^2/s$ are calculated from the arised chloride profiles.

The Ryå-bridge represents the first milestone for HPCs i Denmark. The mix design for the Ryå bridge is given in table 1. In the following years an increasing use of silica fume in concretes for very aggressive environments such as swimming pools began. This was caused by a recognized lack of durability of concrete made with reactive opaline chert from many Danish sand deposits. The observed improvements of the properties of the fresh and the hardened concrete lead to application of silica fume in combination with fly ash in the 500 m long half part of the highway tunnel lining under Guldborgsund. A succesful production of more than 1500 balcony elements of an extreme concrete quality followed. On this basis the concrete mix design for the Great Belt Link, with a specified service life of 100 years, was made.

The Great Belt Link

The design of the Great Belt Link was initiated in 1987. The Great Belt Link represents the most extensive engineering work ever made in Denmark. The Great Belt Link consists of three main structures. A 7 km long bored tunnel with a lining made of 60.000 concrete segments, a double (rails and road) 7 km long low bridge of 68 spans and a 8 km suspension bridge with a maximum world record free span of 1624 m.

The concrete mix may now be considered a typical example of a HPC with a very good durability. The mean compressive strength is in the interval from 50 to 90 MPa but no more than 50 MPa of characteristic strength is taken in to account in the structural design. A typical mix design for the Great Belt concrete is given in table 1.

Motorway Bridge

The first Danish bridge with a specified strength of more than 50 MPa namely 75 MPa was made in 1991-1992. The structural design was traditional taking no advantage of the high strength. Again the bridge was made as an experimental bridge with the primary objective of demonstrating that high strength may be obtained and maintained in a reliable way on site. The experiment was on the whole a success. The mix design for the bridge concrete is given in table 1.

Truss Pedestrian girder

The first structure in Denmark taking advantage in the design of the specified characteristic strength of 75 MPa was a truss girder with a span of 30 m. The girder, which had external prestressing, was produced for the exhibition TeknoVision held in Copenhagen by the Danish Society of Civil Engineers in 1992, and then transported to its final position in Jutland by train. The mix design for the truss girder concrete is given in table 1.

Øresund Link

At present the initial phases of the Øresund Link, which will connect the Danish island of Zealand with Sweden, have been undertaken. The design of this major infrastructural scheme includes the specification of HPC. Special attention has been given to the durability of the concrete structures, whereas the strength level requirements are moderate.

CONCLUSION

In the paper the main areas of research in HPC in Denmark have been outlined. This research includes material studies as well as up to full size experimental bridges. The experiences gained from these, as well as studies from abroad, have led to the specification of HPC for use in main elements of the two largest infrastructural schemes undertaken in Denmark at present. It is however evident that further studies are needed in the future in order to establish a practice of specification of HPC for more general application. Below are listed some of the principal problems which should be addressed in future studies:

Understanding of the mechanisms of the strength loss of silica concretes.

Develloping mix design methods which include the workability as one of the main parameters and thereby extending the possibility of designing pumpable HPC etc.

As the normal Mohr-Coulomb failure condition has been shown not to be valid for HSC, an effort should be made in order to formulate failure criteria for these concretes. This could improve the understanding of ductility of HSC and ensure that reinforcement arrangements with adequate confinement can be specified consistantly.

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Table 1: Examples of mix designs for Danish projects with HPC

Structure/ Parameter	Ryå Bridge	Guldborgsund Tunnel segment no 2 of 2	High strength concrete experimental housing project	1600 Balcony elements for Høje Gladsaxe	The Great Belt Link	Motorway Bridge 70-0030	Pedestrian Truss Girder
Year	1981-82	1987	1986-87	1986-87	1988-1995	1991-92	1992
Approx. m^3	50	$2 \cdot 10^4$	100	2500	$1 \cdot 10^6$	800	75
Composition							
Cement, kg/m^3	302	275	453	320	330	332	330
Aggregates, kg/m^3	1854	1840	1855	1801	1803	1870	1905
w/b-ratio	0.35	0.42	0.21	0.28	0.34	0.31	0.33
fa/b-ratio	0.0	0.15	0.0	0.18	0.10	0.12	0.08
ms/b-ratio	0:13	0.04	0.13	0.10	0.05	0.08	0.08
sa/st-ratio	0.56	-	0.75	0.75	-	0.57	0.47
p+sp/b-ratio	-	-	0.013	0.013	-	0.018	0.010
air content, %	5.1	7.0	1.0	5.5	7.0	1.5	1.5
$f_{c,28}$, MPa	62	45	102	75	60	80	75

Abbreviations: w/b: the weight ratio between total effective water and total binder (cement + fly ash + silica fume); fa/b: the weight ratio between fly ash and total binder; ms/b: the weight ratio between silica fume and total binder; sa/st: the weight ratio between fine aggregates (less than 4 mm) and coarse aggregates; p+sp/b-ratio: the weight ratio between the dry matter of the plasticizer plus superplasticizer and total binder; $f_{c,28}$: the cylinder compressive strength at 28 days.

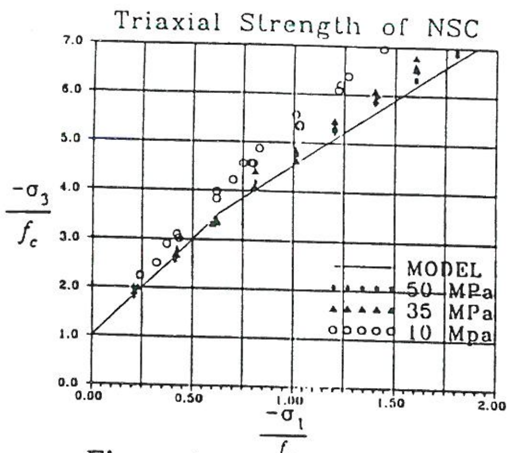

Figure 1

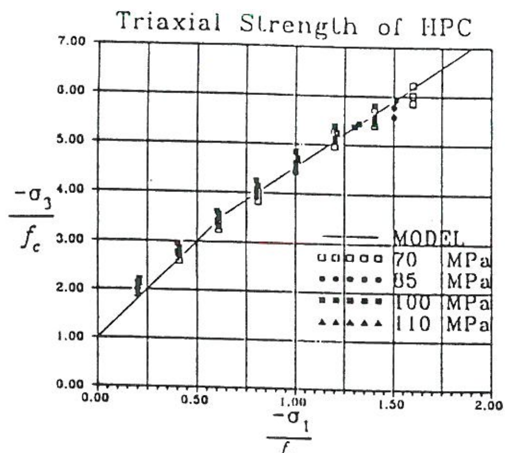

Figure 2

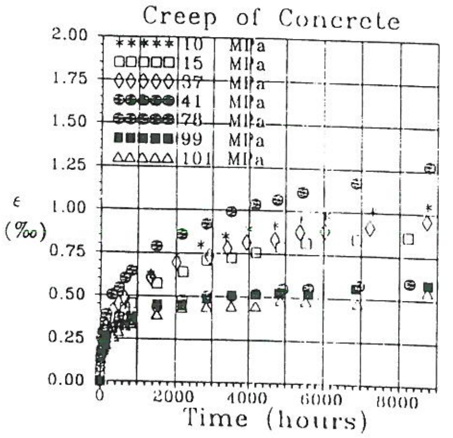

Figure 3

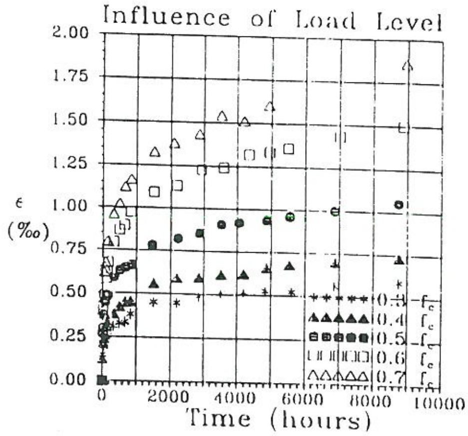

Figure 4

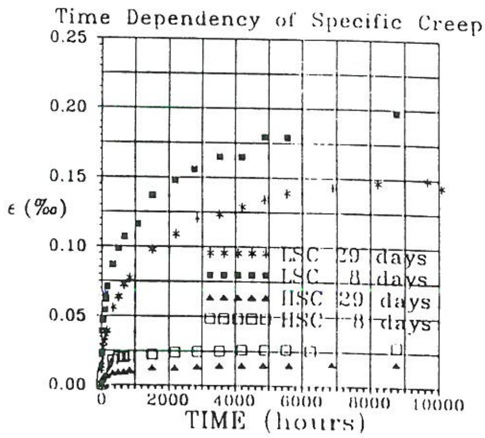

Figure 5

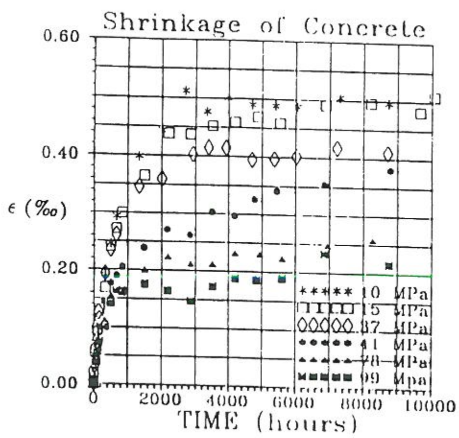

Figure 6

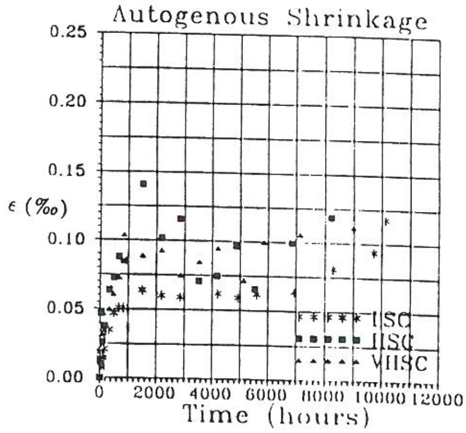

Figure 7